DIS with Neutrinos: Now and When

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Neutrino scattering experiments have been studying QCD with DIS for around 40 years. An example of the more recent DIS studies of QCD with neutrinos is the NuTeV ν-Fe experiment that used the high-energy TeVatron neutrino beam. The problem the community faces in trying to study QCD with modern neutrino data is that there is no experimentally verified way to scale neutrino-nucleus (for example, Fe) results to the equivalent neutrino-nucleon values and there are now indications that nuclear effects in neutrino nucleus interactions might be different than those measured in charged-lepton nucleus scattering. To better understand this situation, the MINERνA neutrino-nucleus scattering experiment at Fermilab and eventually the much more precise neutrino factory scattering experiments will yield a more thorough A-dependent study of nuclear PDFs and these correction factors.

1 Introduction

Neutrino scattering plays an important role in extraction of fundamental parton distribution functions (PDFs) because only neutrinos can resolve the flavor of the nucleon's constituents: ν interacts with d, s, $\overline{u}$ and $\overline{c}$ while the $\overline{\nu}$ interacts with u, c, $\overline{d}$ and $\overline{s}$. The weak current's unique ability to "taste" only particular quark flavors significantly enhances the study of parton distribution functions. High-statistics measurement of the nucleon's partonic structure, using neutrinos, will complement studies with electromagnetic probes.

Large data samples, and dedicated effort to minimizing beam-related systematics will allow neutrino experiments to independently isolate all the structure functions $F_1^{\nu N}(x,Q^2)$, $F_1^{\bar{\nu} N}(x,Q^2)$, $F_2^{\nu N}(x,Q^2)$, $F_2^{\bar{\nu} N}(x,Q^2)$, $xF_3^{\nu N}(x,Q^2)$ and $xF_3^{\bar{\nu} N}(x,Q^2)$ for the first time. By taking differences and sums of these structure functions, specific parton distribution functions in a given (x,Q^2) bin can in turn be determined. With the manageable systematic uncertainties expected in current and future experiments, neutrino experiments can dramatically improve the isolation of individual PDFs by measuring the full set of ν and $\bar{\nu}$ structure functions. Extracting this full set of structure functions will rely on the y-variation of the structure function coefficients in the expression for the cross-section. In the helicity representation, for example:

$$\begin{aligned}\frac{d^2\sigma^\nu}{dxdQ^2} \quad &= \quad \frac{G_F^2}{2\pi x}\Big[\frac{1}{2}\left(F_2^\nu(x,Q^2) + xF_3^\nu(x,Q^2)\right) + \\ &\quad \frac{(1-y)^2}{2}\left(F_2^\nu(x,Q^2) - xF_3^\nu(x,Q^2)\right) - \\ &\quad 2y^2F_L^\nu x,Q^2)\Big]. \end{aligned} \tag{1}$$

By analyzing the data as a function of $(1-y)^2$ in a given (x, Q^2) bin, all six structure functions can be extracted.[1]

2 Neutrino Iron Scattering Results

Due to the weak nature of the neutrino interaction, to acquire significant statistics the use of heavy nuclear targets is unavoidable. This complicates the extraction of free nucleon PDFs because corrections must be applied to the data to convert from the nucleus A to a nucleon. The results of the latest study of QCD using neutrino scattering comes from the NuTeV experiment [1]. The NuTeV experiment accumulated over 3 million ν and $\overline{\nu}$ events in the energy range of 20 to 400 GeV off a manly Fe target. The main points are that the NuTeV cross section agrees with the CCFR values (obtained using the same detector) for values of $x_{Bj} \leq 0.4$ but is systematically higher for larger values of x_{Bj} culminating at $x_{Bj} = 0.65$ where the NuTeV result is 20% higher than the CCFR result. NuTeV agrees with charged lepton data for $x_{Bj} \leq 0.5$ but there is increasing disagreement for higher values. Although NuTeV F_2 and xF_3 agree with theory for medium x, they find a different Q^2 behavior at small x and are systematically higher than theory at high x. These results can be summarized in four main questions to ask subsequent neutrino experiments:

- At high x, what is the behavior of the valence quarks as x $\rightarrow$ 1.0?
- At low W, what is happening in the transition region between resonance production and the DIS regions?
- At all x and Q^2, what is yet to be learned if we can measure all six ν and $\overline{\nu}$ structure functions to yield maximal information on the parton distribution functions?
- At all x, how do nuclear effects with incoming neutrinos differ from nuclear effects with incoming charged leptons?

This last item highlights an overriding question when trying to get a global view of structure functions from both neutrino and charged-lepton scattering data. How do we compare data off nuclear targets with data off nucleons and, the associated question, how do we scale nuclear target data to the comparable nucleon data. In most PDF analyses, the nuclear correction factors were taken from $\ell^{\pm}$-nucleus scattering and used for both charged-lepton and neutrino scattering. Recent studies by a CTEQ-Grenoble-Karlsruhe collaboration have shown that there my indeed be a difference between the charged-lepton and neutrino correction factors.

The data from the high-statistics ν-DIS experiment, NuTeV summarized above, was used to perform a dedicated PDF fit to neutrino–iron data.[2] The methodology for this fit is parallel to that of the previous global analysis,[3] *but* with the difference that only Fe data has been used and no nuclear corrections have been applied to the analyzed data; hence, the resulting PDFs are for a proton in an iron nucleus - nuclear parton distribution functions.

By comparing these iron PDFs with the free-proton PDFs (appropriately scaled) a neutrino-specific heavy target nuclear correction factor R can be obtained which should be applied to relate these two quantities. The nuclear correction factors for $F_2^{\nu Fe}$ and $F_2^{\bar{\nu} Fe}$ at $Q^2 = 5$ GeV^2 and 20 GeV^2 derived in this analysis and labeled A2 are shown in Fig. 1.

[1] Note that for this type of parton distribution function study, anti-neutrino running will be essential.

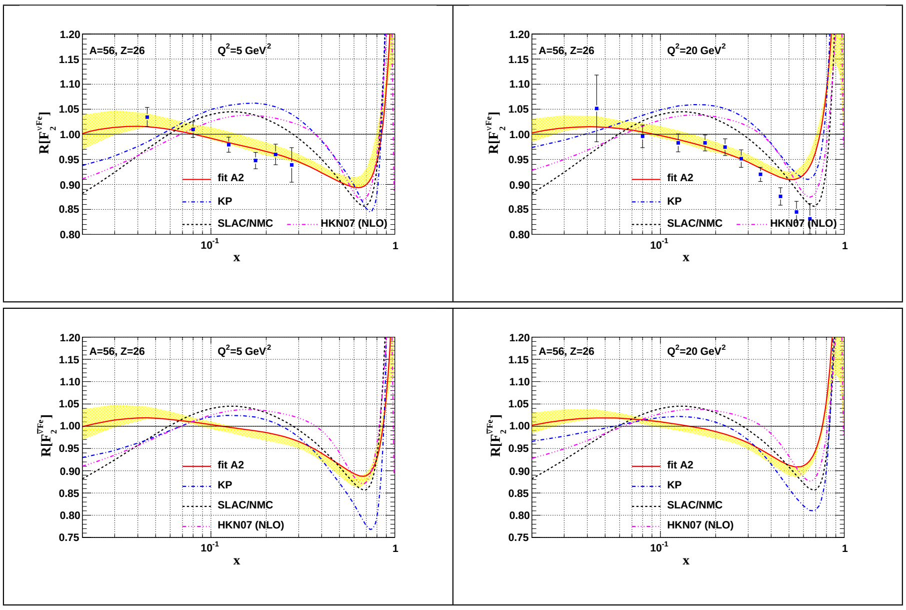

Figure 1: Nuclear correction factor R for the structure function F_2 in neutrino and anti-neutrino scattering from Fe for $Q^2 = \{5, 20\}\,\mathrm{GeV}^2$. The solid curve shows the result of the nCTEQ analysis of NuTeV data; the uncertainty from the fit is represented by the shaded (yellow) band. For comparison the correction factor from HKN07 (dashed-dotted line),[4] and the SLAC/NMC parametrization (dashed line) are shown.

The SLAC/NMC curve in the figures has been obtained from an A and Q^2-independent parameterization of calcium and iron charged–lepton DIS data.[3] Although the results of this analysis have general features in common with the SLAC/NMC (charged-lepton) parameterization, the magnitude of the effects and the x-region where they apply are quite different. The present results are noticeably flatter than the SLAC/NMC curves, especially at moderate-x where the differences are significant. The general trend is that the anti-shadowing region is shifted to smaller x values, and any turn-over at low x is minimal given the PDF uncertainties. More specifically, there is no indication of "shadowing" in the NuTeV neutrino results,particularly at low-Q^2 In general, these plots suggest that the size of the nuclear corrections extracted from the NuTeV data are smaller than those obtained from charged lepton scattering (SLAC/NMC).

3 Continuing the Study of DIS ν - A Interactions

To eventually be able to include neutrino-nucleus DIS scattering results in a global QCD fit, understanding the neutrino-nucleus nuclear effects is essential. The CTEQ study of the iron PDFs provides a foundation for a general investigation (involving a variable A parameter) that can address this topic. However the results from a much wider variety of nuclear targets will be needed to definitively answer this question. There is one experiment currently taking data and a future neutrino DIS experiment that will have the small statistical and systematic errors needed to measure all six of the neutrino structure functions mentioned at the beginning of this article.

3.1 The MINERνA Experiment

The MINERνA experiment [5, 6], a collaboration of elementary-particle and nuclear physicists, is performing a hight-statistics, systematic study of neutrino nucleus interactions. The overall goals of the experiment are to measure absolute exclusive cross-sections and study nuclear effects in ν - A interactions with He, C, O, Fe and Pb nuclear targets. For QCD oriented studies, they are planning systematic studies of the resonance-DIS transition region and the low Q^2 DIS region including the extraction of high-x_{Bj} parton distribution functions. The MINERνA experiment recently finished their low-E_ν exposure and will begin taking data with a higher energy beam (= higher percentage DIS events) next year. More details can be found in the contribution of Joel Mousseau to these proceedings.

3.2 A Neutrino Factory Study of DIS ν - A Interactions

The baseline design for a Neutrino Factory [7] includes the need for one or more near detectors. The near detectors must be designed to carry out measurements essential to the sensitivity of the oscillation-physics program. However, in addition, the intense neutrino beam delivered by the Neutrino Factory makes it possible to carry out a unique neutrino scattering physics program at a near detector. This program includes fundamental electroweak and QCD physics.

The unprecedented neutrino fluxes available for the Neutrino Factory program will allow the collection of a large number of inclusive neutrino charged current (CC) interactions. The combination of this substantial flux with a finely segmented near detector offers a unique opportunity to produce a range of neutrino scattering physics measurements, in addition to those needed by the long base line oscillation program.

4 Conclusions

The NuTeV ν-Fe experiment is the most recent high-statistics DIS experiment that also has produced a very detailed study of systematic errors in the form of a covariant error matrix. There are inconsistencies of the NuTeV results with other ν-nucleus experiments particularly at low- and high-x. To be able to combine these NuTeV results with other DIS experiments, a way of converting ν-Fe to ν-nucleon has to be determined. Using these results from the NuTev neutrino Fe experiment, nuclear effects of charged current deep inelastic neutrino-iron scattering were studied by the nCTEQ collaboration in the frame-work of a χ^2 analysis and a set of iron nuclear correction factors for iron structure functions were extracted. Comparing these results with correction factors for $\ell^\pm$-iron scattering it was determined that, except for very high x_{Bj}, the neutrino correction factors differ in both shape and magnitude from the correction factors for charged-lepton scattering. For the near future, the nuclear correction factors R are being measured over a wider range of A and with reduced errors by the MINERνA experiment in the NuMI beam. Further in the future, a neutrino factory with very intense and well-known neutrino beams will provide a direct comparison between nuclear targets and nucleon (liquid hydrogen and deuterium) targets.

References

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